UNIVERSITY OF TECHNOLOGY, SYDNEY

Model-Aided State Estimation for Quadrotor Micro Aerial Vehicles

by

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Declaration of Authorship

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Abstract

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Due to their manoeuvrability, compactness and vertical take-off and landing capability, quadrotor Micro Aerial Vehicles (MAV) are ideally suited to assist or replace humans in a host of tasks in urban and indoor environments that would otherwise be hazardous, tedious or expensive. However, obtaining reliable pose estimates to perform these tasks safely and efficiently is a significant challenge due to the limited accuracy of GPS in such environments. This thesis presents algorithms for pose estimation of quadrotor Micro Aerial Vehicles (MAVs) operating in GPS-denied environments. The main contributions of the thesis stem from the use of the dynamic model describing the motion of a quadrotor as an additional source of information during state estimation.

A state estimator design for quadrotor MAVs that only employs consumer grade inertial sensors is first proposed. Two major improvements to the conventional inertial only state estimators for MAVs are demonstrated. First, it is shown that incorporating an appropriate dynamic model improves the accuracy of the MAV attitude estimate. Second, in contrast to the conventional designs, it is shown that the new estimator provides a drift free estimate of the horizontal components of the quadrotor body frame velocity. These velocity estimates can be exploited to substantially improve the stability and controllability of a quadrotor MAV.

In addition to inertial sensors, monocular cameras provide an excellent source of information that can be used for the MAV state estimation task. The complementary nature of visual and inertial information means that a fusion of the two information sources can improve the accuracy and robustness of the state estimation algorithms. This thesis demonstrates that further improvements in accuracy and robustness can be obtained by incorporating the quadrotor dynamic model into visual-inertial fusion algorithms. The resulting state estimator design is capable of producing reliable pose estimates even when the quadrotor MAV is travelling at a constant velocity, a case which is known to be difficult to handle with conventional algorithms. A theoretical analysis using Lie derivatives is presented to verify this improvement in observability. Extensive simulations and experiments in a number of practical situations are presented to demonstrate the effectiveness of the proposed methodology and to demonstrate that it outperforms conventional visual-inertial fusion methods.

Employing the dynamic model to aid the state estimation can also be extended to deal with wind disturbances that would otherwise hamper the performance of lightweight quadrotor MAVs. This thesis demonstrates that explicit modelling of the effects of wind on the quadrotor dynamics enables the simultaneous estimation of the vehicle pose and two components of wind velocity, using only a monocular camera and an inertial measurement unit. This design is validated through a non-linear observability analysis and extensive simulations that makes use of a realistic wind model. Experimental results in a controlled lab environment are also presented to demonstrate the effectiveness of the proposed state estimator.

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Abbreviations

BLDC	Brush-Less Direct Current
CAE	Conventional Attitude Estimator
C-VIF	Conventional Visual-Inertial Fusion
EKF	Extended Kalman Filter
GPS	Global Positioning System
ID	Inverse Depth
IMU	Inertial Measurement Unit
MAV	Micro Aerial Vehicle
MAVE	Model-aided Attitude and Velocity Estimator
MA-VIF	Model-Aided Visual-Inertial Fusion
MEMS	Micro-Electro-Mechanical Systems
NED	North, East, Down
PID	Proportional, Integrative, Derivative
PSD	Power Spectral Density
PTAM	Parallel Tracking And Mapping
RGB	Red, Green, Blue
RMS	Root-Mean-Square
SIFT	Scale-Invariant Feature Transform
VIF	Visual-Inertial Fusion
VSLAM	Visual Simultaneous Localization and Mapping
VTOL	Vertical Take-off and Landing
WGN	White Gaussian Noise
wMA-VIF	Wind incorporated Model-Aided Visual-Inertial Fusion

Nomenclature

	General Formatting Style
$f(\cdots)$	A scalar valued function
$\boldsymbol{f}(\cdots)$	A vector valued function
$[\cdot]_x$	The x component of a vector
$[\cdot]_y$	The y component of a vector
$[\cdot]_z$	The z component of a vector
${}^{B}[\cdot]$	The frame of expression of a vector
$\dot{[\cdot]}$	The time derivative of a variable
$[\cdot]^T$	Transpose of a vector or a matrix
$\\|\cdot\\|$	The magnitude of a vector
$E[\cdot]$	The expectation of a random variable
$[\cdot](p,q)$	The $(p,q)^{th}$ element or block of a matrix
$[\cdot](p,:)$	The p^{th} row or row block of a matrix
	Specific Symbol Usage
$\mathbf{0}_n$	$n \times n$ all zero matrix
$\{E\}$	Earth fixed inertial coordinate frame
$\{B\}$	Body coordinate frame
$\boldsymbol{a}$	A vector containing the measurement of accelerometer triad
${}^{B}_{E}R$	Rotation matrix to transform a vector from {B} to {E}
c_Q	propeller torque coefficient
c_T	Lumped thrust coefficient
d	Distance from the centre of mass of the quadrotor to propeller hub

d_i	Induced drag coefficient
$\bar{D}_L$	Lumped parameter drag coefficient matrix
$\boldsymbol{e}_i$	The i^{th} unit vector
$\boldsymbol{F}$	Sum of aerodynamic forces affecting the quadrotor MAV
f_T	The magnitude of the thrust vector
$\boldsymbol{g}$	Gravity vector
g	Magnitude of gravity vector
$\boldsymbol{h}_{vp}$	VSLAM position estimates
$\boldsymbol{h}_{vo}$	VSLAM orientation estimates
$\boldsymbol{I}_n$	$n \times n$ identity matrix
J	Inertia matrix of the quadrotor MAV
k_1	Lumped drag coefficient
$\boldsymbol{M}$	Sum of aerodynamic moments affecting the quadrotor MAV
m	Mass of the quadrotor MAV
M_i	i^{th} motor
$\boldsymbol{p}$	Position of the quadrotor MAV
r_p	The radius of a propeller
$\boldsymbol{u}$	Inputs to a dynamic system
$\boldsymbol{v}$	Velocity of the quadrotor MAV
$\boldsymbol{v}_w$	Velocity of the wind
$\boldsymbol{v}_\infty$	Free stream velocity of the quadrotor MAV
$\boldsymbol{X}$	State of a dynamic system
$\boldsymbol{x}_i$	3D position of an environmental feature in $\{E\}$
$\boldsymbol{y}$	Measurements of a dynamic system
ϖ_i	Rotational rate of i^{th} propeller
$\boldsymbol{\Theta}$	Orientation of $\{B\}$ with respect to $\{E\}$
ϕ	Roll angle
θ	Pitch angle
ψ	Yaw angle
$\boldsymbol{\Omega}$	Instantaneous rotational rate of $\{B\}$ with respect to $\{E\}$
Ξ	Matrix that transforms instantaneous rotational rates to Euler rates

$\boldsymbol{\omega}_g$	A vector containing the measurement of gyroscope triad
$\boldsymbol{\beta_g}$	Gyroscope bias
$\boldsymbol{\beta_a}$	Accelerometer bias
$\boldsymbol{\eta_g}$	Gyroscope measurement noise
$\boldsymbol{\eta_{\beta g}}$	Gyroscope bias drift noise
$\boldsymbol{\eta_a}$	Accelerometer measurement noise
$\boldsymbol{\eta_{\beta a}}$	Accelerometer bias drift noise
$\boldsymbol{\eta_q}$	Process noise
$\boldsymbol{\eta_r}$	Measurement noise
$\boldsymbol{\eta_v}$	Process noise of the quadrotor translational dynamics
$\boldsymbol{\eta_p}$	Noise in VSLAM position estimates
$\boldsymbol{\eta_o}$	Noise in VSLAM orientation estimates
$\boldsymbol{\eta_\lambda}$	VSLAM scale drift noise
$\boldsymbol{\eta_w}$	Wind velocity drift noise
Υ	A 2×3 matrix consisting of the first three rows of $\boldsymbol{I}_3$
$\boldsymbol{\Gamma}$	3×3 matrix of all zeros with the (3,3) element set to one.
λ	Scale of VSLAM estimates
Λ	3×3 Identity matrix with the (3,3) element set to zero

Glossary of Terms

Attitude	The combination of roll and pitch angles.
Consistent estimates	Estimates whose errors agree with the error covariance bounds predicted by the estimator.
Features	Distinctly identifiable points in an image of a 3D environment.
Free stream velocity	Velocity of an object with respect to the air stream around it.
Induced drag	A drag force that occurs due to the redirection of an air stream by a moving object.
Inertial Sensors	Sensors based on inertia. Common examples are accelerometers and gyroscopes.
Model-aided state estimation	Employing dynamic models and kinematic constants of a platform to aid the state estimation processes.
Monocular VSLAM	VSLAM algorithms that only employs measurements from a RGB camera.
Multi-rotor	A category of aerial vehicles with three or more lift producing propellers.
Observability	The ability to uniquely determine the state of a dynamic system with a causal sequence of measurements.
Pitch	Second Euler angle caused by a rotation around body frame y axis.
Pose	The combination of position and orientation of an object in 3D space with respect to a reference coordinate frame.
Quadrotor	An aerial vehicle with four lift producing propellers.

Roll	Third Euler angle caused by a rotation around body frame x axis.
Scale	The ratio between the true and estimated map by a monocular VSLAM algorithm.
Visual-inertial fusion	The combination of information obtained from visual and inertial sensors to estimate states of interest.
Yaw	First Euler angle caused by a rotation around body frame z axis.